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Abstract: Fort Bragg, North Carolina includes over 65,000 acres of longleaf pine forest, which is primary habitat for the endangered red-cockaded woodpecker (RCW). Effective management of the RCW depends on effective management of the longleaf pine forest. However, growth and yield models available in the geographic area that includes Fort Bragg over-predict stand growth and produce unrealistic projections of future stand conditions. Among these models is the Southern Variant of the Forest Vegetation Simulator (FVS), which was developed and is maintained by the USDA Forest Service. The FVS framework covers all forested land in the contiguous 48 states and coastal Alaska, but there is considerable variation in the extent to which the accuracy of regional FVS variants has been tested by local users. While FVS is of limited use on Fort Bragg in its current form, forest managers in the installation recognized the high potential of FVS as a management tool. As a result, a scheduled periodic inventory of Fort Bragg was designed so the data could be used to test and calibrate selected FVS submodels. This paper describes data considerations, evaluation methods, and re-calibration procedures used to produce a "Fort Bragg version" of FVS.

Keywords: FVS, simulation, growth models, longleaf pine, model validation

Introduction

The Fort Bragg military reservation in North Carolina includes over 65,000 acres of longleaf pine (*Pinus palustris* Mill.) forest, one of the largest remaining contiguous tracts of the type. It is also home to one of the largest populations of the endangered red-cockaded woodpecker (*Picoides borealis*). Fort Bragg and adjacent properties form a primary core population in the Sandhills Recovery Unit (U.S. Fish and Wildlife Service 2003). As a result, the red-cockaded woodpecker (hereafter, RCW) population at Fort Bragg is intensively monitored and managed. To manage the RCW effectively, it is necessary to manage its habitat. Management goals that include maintenance of stand composition and structure are accomplished through a combination of silvicultural manipulations and prescribed fire. Inventory data are required to assess the suitability of forest conditions according to the RCW recovery guidelines (U.S. Fish and Wildlife Service 2003).

An installation-wide forest inventory was conducted on Fort Bragg in the early 1990s. The data provided by this inventory were to be used for assessment of the quality and quantity of suitable RCW habitat, as well as for identification of acreage in need of restoration treatments. In the interest of planning for future growth of the forest and development of military facilities, the inventory contract required 10-year growth projections, at the stand level, for the entire installation. However, growth projections provided by the contractor appeared to be unrealistically high when compared with the stocking levels known to be attainable on the dry, sandy soils characteristic of Fort Bragg and much of the Carolina Sandhills. In subsequent evaluations, other growth models showed similar tendencies. When planning for a new inventory started in 2000, no suitable growth model had yet been found.

The Forest Vegetation Simulator (FVS) is a distance-independent, single-tree growth model that is the standard stand projection tool used by the USDA Forest Service (Johnson 1997). During the 1990s, the Forest Service made substantial improvements to FVS, including addition of the Suppose interface (Crookston 1997) and development of a new Southern variant of the model (Donnelly et al. 2001). Preliminary testing of the Southern variant indicated that it, too, would overestimate growth on Fort Bragg. However, the other capabilities offered by the FVS framework – such as the ability to simulate silvicultural manipulations and linkage to the Stand Visualization System (McGaughey 1998) – suggested that FVS could provide a useful framework under which a suitable growth model for Fort Bragg could be developed.

As a result, the 2000 Fort Bragg inventory was modified to include variables needed for evaluation and, if necessary, re-fitting FVS submodels. Our objective is to develop a "Fort Bragg version" of FVS. In this paper we describe the inventory design, data collection, and model development that have been accomplished to date. Although designed specifically for Fort Bragg, the process is applicable to many situations where local evaluation and fine-tuning of FVS is needed.

Methods and Preliminary Results

Inventory Design and Data Collection

FVS variants are composed of a series of linked submodels (Figure 1). Each submodel consists of one or more equations, depending on program logic. This allows submodels to be evaluated and modified independently. Therefore, we emulated the workflow process used by the USDA Forest Service, Forest Management Service Center during the development of the Southern and other FVS variants.

Because we were primarily concerned with projection of large tree growth and mortality, we elected not to modify the establishment and small tree growth models of the Southern Variant. In addition, we restricted our species list to the common pines found on Fort Bragg: longleaf pine, loblolly pine (*P. taeda* L.), slash pine (*P. elliottii* Engelm.), pond pine (*P. serotina* Michx.), and shortleaf pine (*P. echinata* Mill.). Although over 50 tree species occur on Fort Bragg, non-pine species are typically a minor component of the upland stands that comprise most of the forest. Most stands are regenerated naturally, but all of the slash pine is in plantations.

Using documentation of the Southern Variant (Donnelly 1997), we developed a list of measured and computed variables necessary for fitting the submodels to Fort Bragg data. This list was used when writing specifications for the 2000 inventory contract. The Southern variant was developed using a variety of data sources and, as a result, considerable effort was required to bring the data into a common format (D. Donnelly, pers. comm.). By integrating the FVS-ready variables into the inventory design, we minimized the amount of effort required for data development (Figure 1).

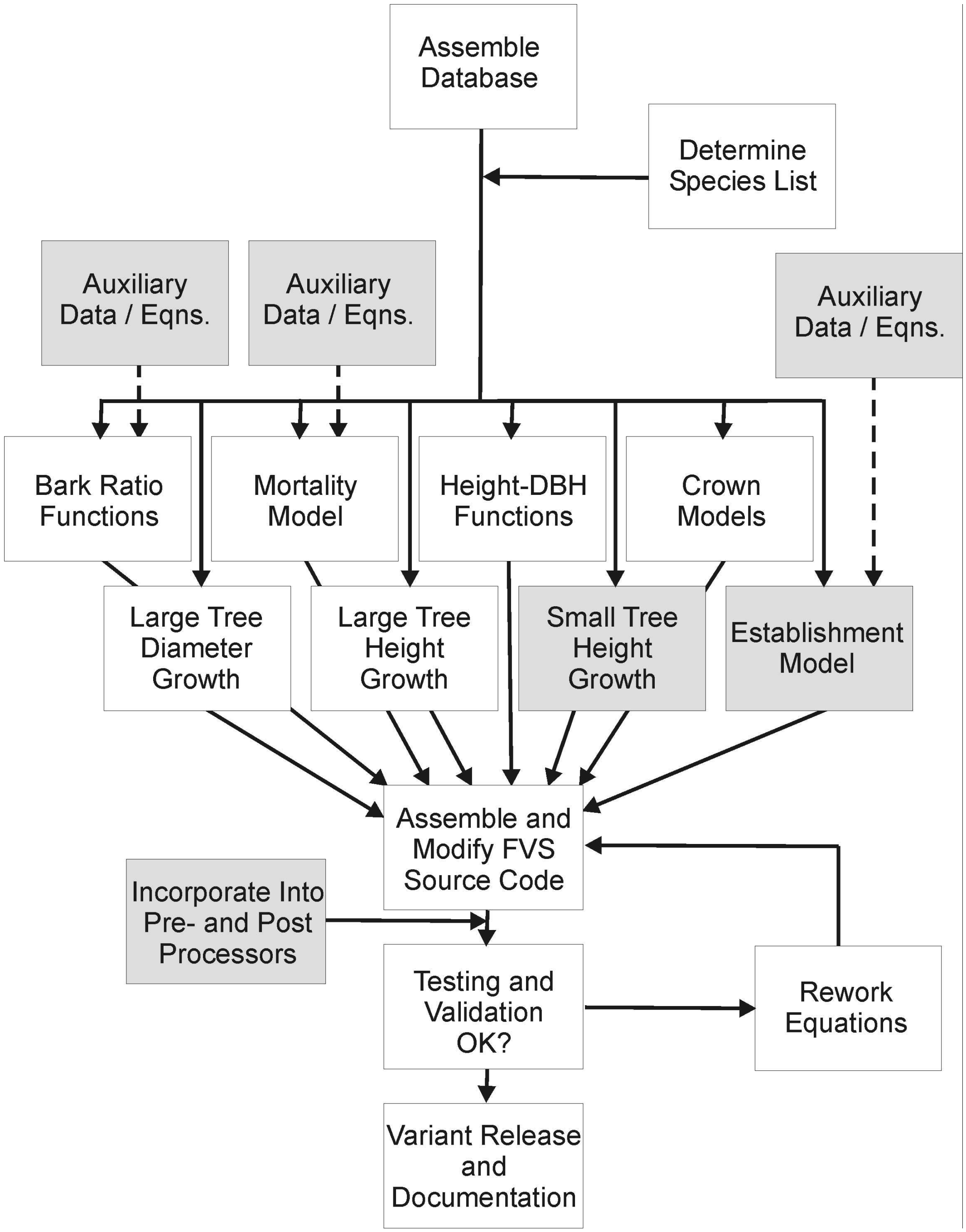

Figure 1. Work process for development of a Forest Vegetation Simulator (FVS) variant (after Johnson et al. 1998). Shaded steps are not needed in development of the Fort Bragg Variant.

The forested area of Fort Bragg was delineated into stands, with a minimum polygon size of 5 acres, using digital orthophotography and GIS. This yielded 1,384 stands, ranging up to 600 acres in size. Stands in firing ranges and ordinance impact areas could not be inventoried because of potential danger to crews and were assigned to surrogate stands that could be inventoried, based on airphoto analysis of composition and structure.

Measured variables were separated into 3 groups that would be collected at different intensities, depending on plot type designation: 1) **ordinary variables** were measured for every tally tree on every plot, 2) **site tree variables** were measured on one dominant or codominant pine on approximately every other plot, and 3) **intensive variables** were measured on every tree $\geq$ 5 inches dbh on plots designated as intensive measurement plots (approximately 5% of all plots). For example, on ordinary plots, basic data – species, dbh, tree status, dominance class, etc – were measured. On site plots, height, age, and other variables were collected on the dominant tree on the plot. On intensive plots, increment data and crown dimensions were measured on all trees $\geq$ 5 inches dbh. Plot- and tree data were imported into a database and screened for invalid values. A small number of tree records were deleted or modified because of questionable data in one or more fields. After screening the database, the additional variables needed for model development were calculated. Plots were installed at an intensity of approximately 1 plot per acre, depending on stand size. The number of plots per stand ranged from 5 to 83 for a total of 18,121 plots.

Evaluation and Re-fitting Submodels

Our original work plan called for evaluation of the existing submodels in the Southern Variant, using the Fort Bragg data as a validation data set. We intended to re-fit only the submodels that performed poorly against the Fort Bragg data. However, our experience with some of the simple submodels (e.g., height dubbing, which is discussed below) indicated that it would be more efficient to approach each submodel with the intent of re-fitting it with Fort Bragg data. Evaluation of the submodels, as parameterized in the Southern variant, would be done primarily to quantify the difference between submodel versions.

Fitting the simple submodels, such as those used for height dubbing and bark thickness estimation, to Fort Bragg data was straightforward. We found that substantial improvements in model performance were gained by re-fitting these models with the local data. For example, the height-dubbing submodel of the Southern Variant, which uses the Curtis-Arney equation (Equation 1; Curtis 1967, Arney 1985) to supply height for trees without measured height, over-predicted height by nearly 8 ft on average. In addition, height prediction bias varied widely across the range of stem diameter. By re-fitting this equation, we were able to reduce bias to less than $\pm$0.2.ft over most of the range of diameter, with a maximum bias less than $\pm$1.2 ft over any range of stem diameter from 2 to 25 inches (Figure 2).

[1] $$Height = 4.5 + a\left(\exp\left(-bDBH^{c}\right)\right)$$

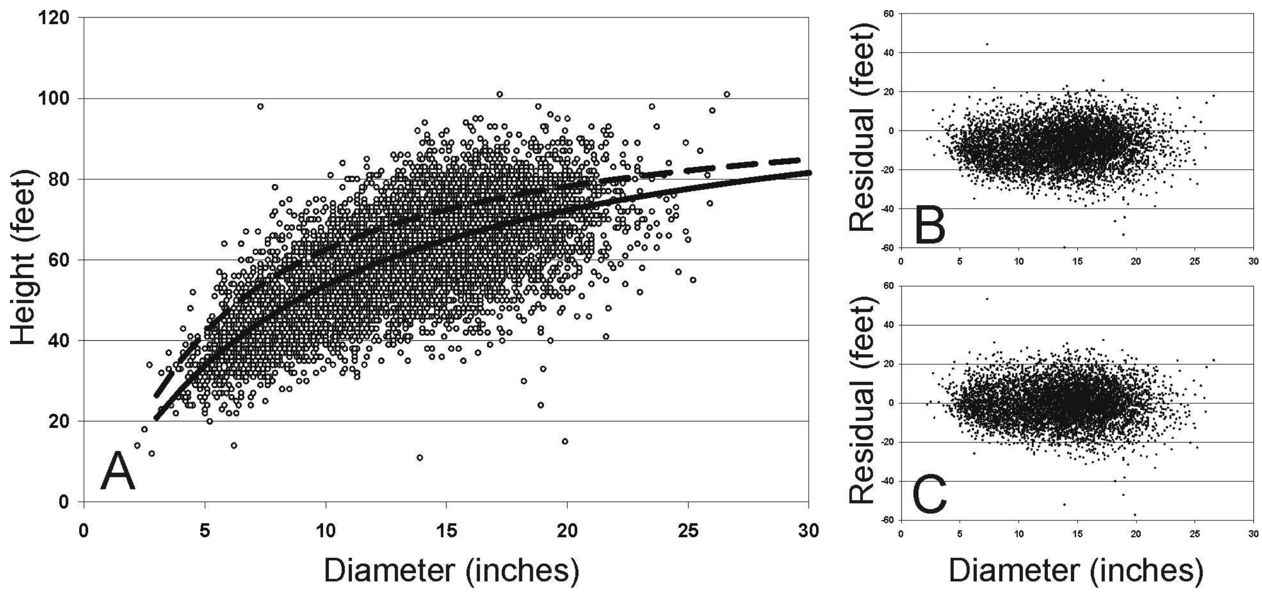

Figure 2. Results of re-fitting the height dubbing model. A. Fort Bragg diameter-height data for 7371 longleaf pines. Dashed curve represents diameter-height relationship for longleaf pine in the Southern Variant, which has a mean over-prediction bias of 7.7 feet on Fort Bragg (B). Solid line represents re-fitted Curtis-Arney equation (Equation 1). Re-fitted equation has less than $\pm$0.2.ft of bias over most of the range of diameter, with a maximum bias less than $\pm$1.2 ft over any range of diameters from 2 to 25 inches (C).

Re-fitting the more complex models has required a different approach. For example, the large tree diameter growth submodel uses a 14-coefficient equation with a mixture of categorical and continuous variables, some of which are log transformed and some of which are not (Table 1). When this equation was fitted to the Fort Bragg data in its complete form, some coefficients were found to be non-significant or have improper sign (e.g., $b_6 > 0$, which suggests a positive relationship between tree diameter increment and plot basal area). In addition, our regressions yielded relatively low R^2 values.

Because the ranges of some variables are relatively small on Fort Bragg as compared to the variability found within the geographic range encompassed by the Southern Variant, we anticipate that they may not be necessary components of the submodels at the local scale. For example, Fort Bragg has rolling terrain and the effects of slope and aspect on forest growth are not readily apparent. Slope position – e.g., moist bottomlands vs. dry ridges – is far more likely to influence stand growth than steepness or aspect. Because both moisture extremes are found on sites with relatively low slope values, any effect of slope on growth is likely to be confounded during equation fitting.

The example below (Figure3) illustrates the amount of variability in diameter increment that is attributable to adding plot basal area as a second predictor (after diameter), using an alternative model form. Adding basal area to the model made a small improvement in R^2 (0.65 vs. 0.73), but it reduced the magnitude of residuals by over 10 percent in some diameter classes. Diameter growth is shown as 5-year increment / starting diameter (A). Fitted lines in (A) show sensitivity of increment to plot-level density, from 30 ft^2 /ac (upper) to 110 ft^2 /ac (lower). Line through residual plot (B) shows residuals means for 2-inch diameter classes (2 to 24 inches). Model form is: Diameter growth = (a + bBA)·(c - (EXP(-dDBH))). R^2 for the model that includes basal area is 0.73.

Table 1. Variables and definitions in the FVS diameter growth submodel (from Donnelly et al. 2001).

	Variable	Description
ln(dds) =	b_0	intercept
	+ b_1 · lndbh	natural log of dbh (at beginning of estimation period)
	+ b_2 · dbh^2	squared dbh
	+ b_3 · lncrwn	natural log of percent crown ratio
	+ b_4 · hrel	relative height
	+ b_5 · isiown	site index for the species
	+ b_6 · plttbac	plot basal area per acre
	+ b_7 · pntbalcx	plot basal area in trees larger than subject tree
	+ b_8 · tanslp	tangent of slope in degrees
	+ b_9 · fcos	function of slope and cosine of aspect
	+ b_{10} · fsin	function of slope sine of aspect
	+ b_{11} · fortype	categorical variable for forest type group
	+ b_{12} · ecounit	categorical variable for ecological unit group
	+ b_{13} · plant	categorical variable for planted stands

* dds = (diameter inside bark at $time_0$ + periodic diameter growth)^2 – diameter inside bark^2

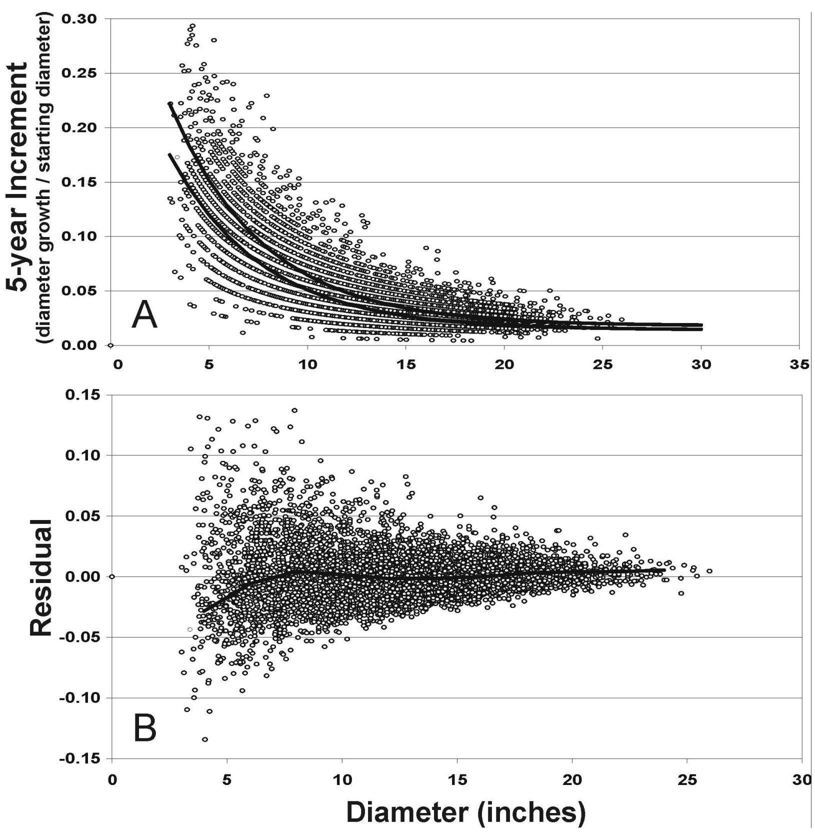

Figure 3. Diameter growth data for longleaf pine.

Mortality Modeling
Perhaps the most challenging part of the model-building process will be development of the mortality submodels. The Southern Variant determines mortality rates 3 ways. When stand density index (SDI) is < 55 percent of the maximum SDI for the forest type, FVS uses a background mortality rate that is a function of diameter and age. If SDI is $\geq$ 55 percent of maximum SDI, mortality is density-dependent. When quadratic mean diameter is < 10 inches, mortality is mediated by maximum SDI, and when quadratic mean diameter is $\geq$ 10 inches, mortality is mediated by a maximum basal area for the forest type. The switch from background mortality to SDI-mediated mortality to basal area-mediated mortality is evident when quadratic mean diameter and stem density projections from an FVS simulation are plotted on a density management diagram (Figure 4).

However, the density-dependent self-thinning dynamic projected in the Southern Variant of FVS may not be realistic for mature longleaf pine stands. Recent work on stand density and dynamics of longleaf pine stands suggests that the expected self-thinning trajectory does not hold for stands with a quadratic mean diameter greater than about 10 inches (Shaw and Long in press). Specifically, FVS projections of longleaf pine growth exceed the maximum limit of the size-density relationship, or “mature stand boundary”, proposed by Shaw and Long (in press) for longleaf throughout its range (Figure 4, Line A).

Size-density data from the 1990s and 2000s Fort Bragg inventories are consistent with the mature stand boundary for longleaf pine. Stands show a decrease in relative density with increasing mean diameter, and, for the largest stands, a decrease in basal area over time. This pattern indicates that factors other than density-dependent mortality, such as Zeide’s (2005) suggestion that mortality outpaces the re-occupation of released growing space, are actually limiting stand density.

It is possible to alter density-dependent stand dynamics “manually” in FVS. Users may supply their own maximum values for SDI and basal area using the SDIMAX and BAMAX keywords in FVS simulations (Van Dyck 2000). It is also possible to modify mortality rates directly using the FIXMORT and MORTMULT keywords (Van Dyck 2000). However, the general behavior of the mortality submodels is the same as with default values, making stand dynamics implied by the mature stand boundary difficult to emulate with keyword-based modifications. Also, keyword-based manipulation of stand growth and mortality is considered an inferior alternative to internal, fitted submodels because users often lack the data required to make meaningful changes to default values. Additional program logic would have to be included because different mechanisms limit stand density at different stages of stand development.

We will attempt to model the mature stand boundary using the existing FVS program logic and model forms. If stand dynamics cannot be modeled adequately using this approach, it may be necessary to modify program logic or create alternative mortality functions. Although the latter case may require fundamental changes to the FVS program code, some efficiency may be gained by developing a single mortality function that works for the entire range of mean diameter.

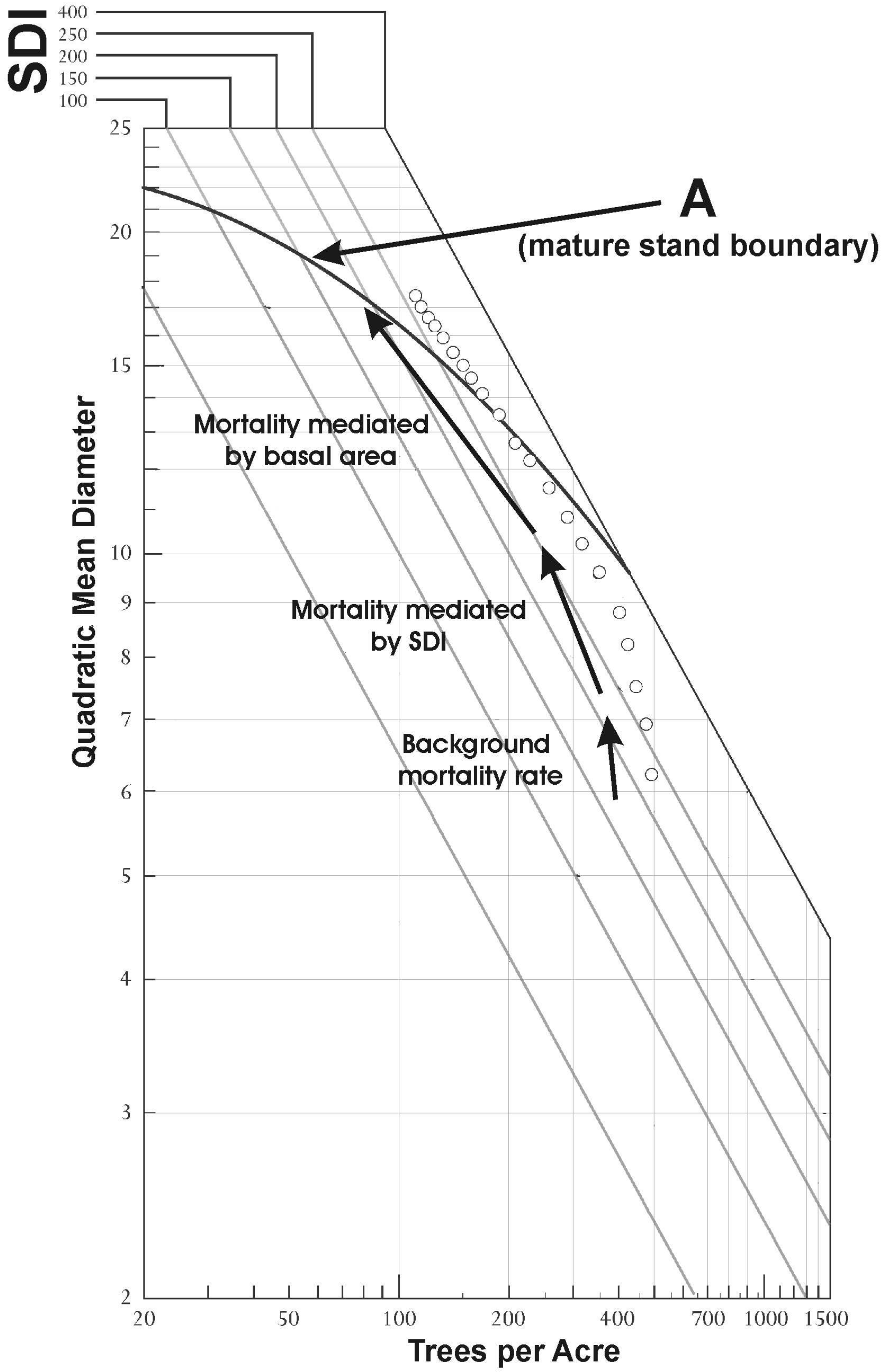

Figure 4. Density management diagram for longleaf pine showing FVS projections of a natural longleaf pine stand from 25 to 125 years of age (open circles). The inflection in stand trajectory between 9 and 11 inches mean diameter results from the shift from SDI-mediated mortality to basal area-mediated mortality in the FVS mortality submodel. Line A is the mature stand boundary for longleaf pine proposed by Shaw and Long (in press).

Discussion

Although we have referred to this effort as development of a local version of an FVS variant, the ultimate goal is to integrate the Fort Bragg submodels into the existing Southern Variant of FVS. This can be accomplished by establishing an administrative code for Fort Bragg, just as National Forests and Districts within National Forests are identified in existing FVS variants. A unique code for Fort Bragg would permit the use of appropriate parameters without alteration of FVS program logic, mostly by amending existing parameter tables.

One potential obstacle to complete integration of the Fort Bragg submodels into the Southern Variant could be a situation where the model form used by FVS was found to be insufficiently flexible when applied to Fort Bragg data. In such a situation it may or may not be possible to integrate suitable models into the existing variant, depending on the degree to which a suitable solution would require modification of the FVS source code. The most likely example is the mortality submodel.

If, for example, the existing mortality submodel is found to be inadequate, there are 2 possible solutions: 1) create a stand-alone variant in which the model forms currently used in FVS have been modified, or 2) propose a comprehensive solution that would add more flexibility to current and future variants. The former solution is undesirable because it would create a variant that would be "frozen" in time and not maintained under the FVS framework – i.e., any updates to the variant would necessarily be initiated by Fort Bragg managers. The latter option would not only meet the goals for development of a variant suitable for Fort Bragg, but could potentially lead to improvements in performance of the Southern Variant by making more flexible submodels available for use in future updates.

Conclusion

Development of a local FVS variant will provide many benefits to land managers at Fort Bragg. Most importantly, the project will satisfy the long-standing need for an accurate, unbiased growth model for the forest. Because of the large amount of data obtained from mature (70+ years old) longleaf pine stands, the model should perform well under stand conditions that provide suitable habitat for the endangered red-cockaded woodpecker. As the forest continues to mature, new growth data may be used to further evaluate submodel parameters and continuously fine-tune the local variant.

Working within the FVS framework takes advantage of many simulation and modeling capabilities that would be cost-prohibitive, if not impossible, to develop from scratch for a local landscape such as Fort Bragg. Integration of the Fort Bragg submodels into the existing Southern Variant provide the added advantage that future enhancements to the FVS framework, such as new keywords and pre- and post-processors, will be accessible to Fort Bragg managers without additional investment. As a result, it is likely that "buying in" to FVS today will continue to provide benefits well into the future.

The process we used for development of the local variant can be repeated wherever adequate data are available. FVS has evolved since the development of the original Prognosis model (Stage 1973), and one mechanism by which this has occurred is user feedback and participation in model refinement.

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